Multiobjective Optimization in Accelerator Design: Future and Present Light Sources

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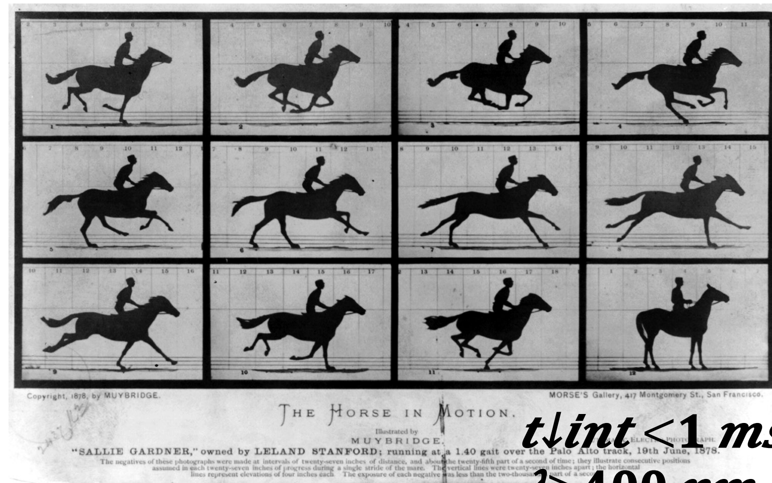
FREE ELECTRON LASERS AND THEIR REQUIREMENTS

Why build a new light source?

Le derby d'Epsom, painting by Théodore Géricault, 1821

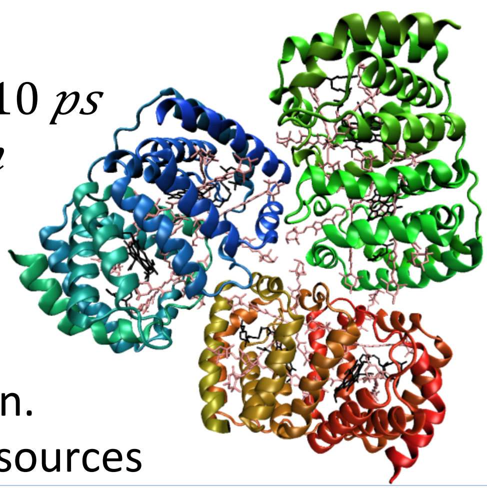
$t_{int} \cong 100\ ms$
$\lambda > 400\ nm$

The horse in motion by Eadweard Muybridge, commissioned by Leland Stanford, 1878



$t_{int} < 1\ ms$
$\lambda > 400\ nm$

$t_{int} \cong 10\ ps$
$\lambda \leq 1\ nm$



3rd gen.
Light sources

The peridinin-chlorophyll-protein light-harvesting complex.

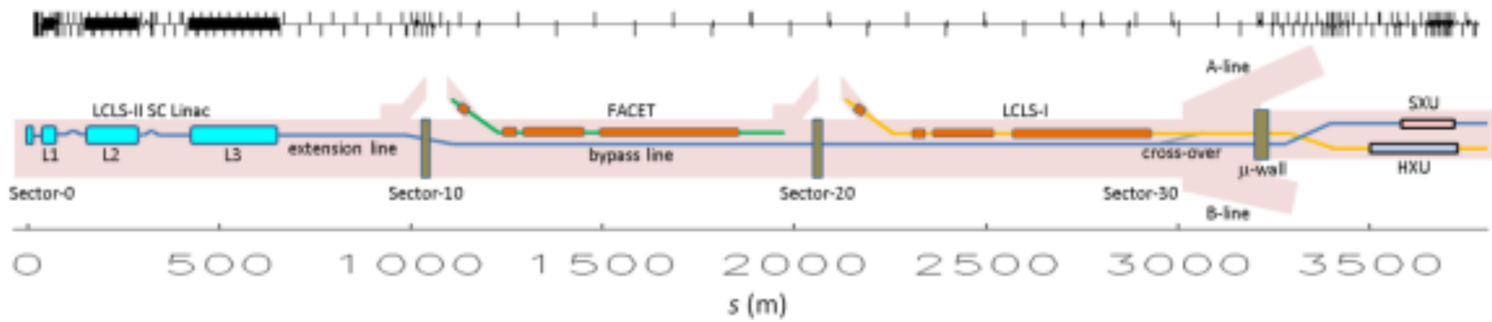
Dynamics

4th gen.
Light sources

$t_{int} < 1-10\ fs$
$\lambda \leq 1\ nm$

Sources
http://upload.wikimedia.org/wikipedia/commons/f/f3/Jean_Louis_Th%C3%A9odore_G%C3%A9ricault_001.jpg
http://upload.wikimedia.org/wikipedia/commons/7/73/The_Horse_in_Motion.jpg
http://upload.wikimedia.org/wikipedia/commons/1/19/Peridinin-chlorophyll-solenoid-1ppr.png

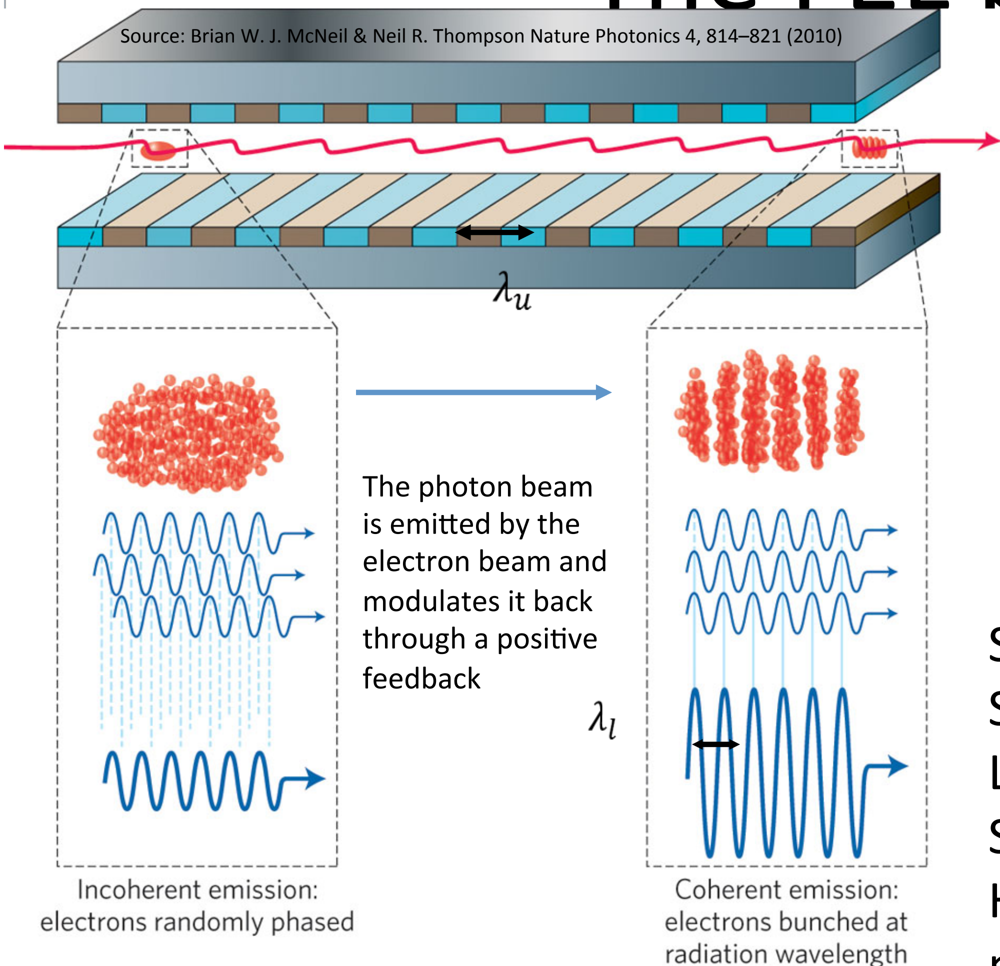
LCLSII
A high repetition rate xray FEL



Linear accelerator (LINAC) driven FELs are a proven tool to produce xray pulses with high power, small bandwidth and short pulse length

LCLS-II will bridge the gap between high repetition rate, low peak power storage rings and low rep. rate, high peak power existing FELs

The FEL process



$$\lambda_l = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)\text{: radiation wavelength}$$

$$K = \frac{eB_0\lambda_u}{2\pi mc}\text{: undulator parameter}$$

$$\rho = \left[\frac{1}{16}\frac{I}{I_A}\frac{K^2[JJ]^2\,\beta}{\gamma^2\epsilon_n\hat{\beta}k_u^2}\right]^{\frac{1}{3}}\text{: FEL (Pierce) parameter}$$

$$P(z)\sim\exp\left(\frac{z}{L_{G0}}\right)\text{: Exponential power gain}$$

$$\mathrm{L}_{G0} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}\text{: Gain length (1-d theory)}$$

Short list of requirements for lasing

Short bunch length σ_z (high peak current I

Low emittance $\epsilon = \epsilon_n/\beta\gamma < \lambda_{light}/4\pi$

Small energy spread $\sigma_E/E < \rho \cong 10^{-3}$

High energy: a few GeV (the simplest but most expensive requirement)

3rd generation light sources

$Power \sim N_{electrons}$

FEL: 4th generation light sources

$Power \sim N_{electrons}^2$

These are not easy to achieve!

Emittance and Peak current

The emittance of a particle beam is a measure of the area it occupies in phase space and is related to the temperature of the beam.

Accelerator physicists always want to minimize it.

The peak current of a beam is especially important for FELs because it drives the FEL instability.

We want to maximize it, or conversely minimize the bunch length for a constant charge.

$$\sigma_x'' + k_{x0}^2 \sigma_x - \frac{3}{2}\frac{N r_c}{(\beta\gamma)^3}\frac{1}{(\sigma_x \sigma_z)}\left(1 - \frac{g}{2}\frac{\sigma_x^2}{\gamma^2 \sigma \ldots\right.$$

$$\sigma_z'' + k_{z0}^2 \sigma_z - \frac{3}{2}\frac{N r_c}{\beta^2 \gamma^5}\frac{g}{\sigma_z^2} - \frac{\epsilon_{zz}'}{z_m^3} = 0$$

M. Reiser
Theory and Design of Charged Particle Beams

At low energies (<100 MeV), space charge forces are important, and they couple the transverse to the longitudinal dynamics.

Compressing the beam can lead to emittance growth (essentially heating) because of this.

Even this coupled nonlinear system does not capture the full dynamics

We need Particle-in-cell (PIC) codes!

COMPUTATION AND OPTIMIZATION

Particle-in-cell codes

Codes that use sample particles to model the beam
The equations of motion for the particles include external (RF, magnets) and internal (collective) fields

Macro-particle approach, multiple real particles are approximated by a single numerical particle, with the same e/m ratio.
We are approaching the 1-1 correspondence fast!
Different models exist for calculating the internal fields, which are computationally harder.

- Particle-Particle: Directly calculate the interactions, slow and needs ~ Np^2 calculations for the self fields
- Particle-Green functions: Calculate the density, solve Maxwell's equations with Green's functions, of order Np*log(Np)
- Particle-Mesh (PIC): Calculate the density, solve Maxwell's equations on a grid, order Np*log(Np)

Examples of codes we use include:
ASTRA, Impact, Elegant, Parmela, WARP etc

Codes used for design

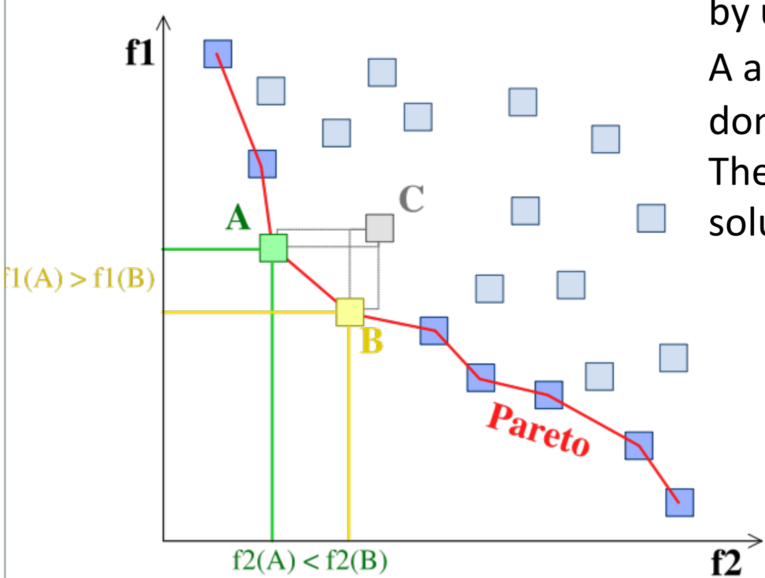
- ASTRA (developed at DESY) is a fast, PIC code that includes most of the relevant physics at low energies.
  - Typical runs 10k-250k macroparticles
  - 5-30 minutes for a single run
  - Good enough for optimization
- IMPACT (developed at LBNL) is a PIC code that has very good parallel performance and is used to validate ASTRA runs by including short scale effects
  - Can scale to real number of particles!
- Both are mature, widely used codes, benchmarked with measurements

Multiobjective optimization

The problem: Find the optima and the trade-offs between 2 competing objectives

The solution: Multi-Objective Algorithms

Photos: wikipedia



The sorting of the solutions is done by using the concept of dominance.

A and B dominate C, but A and B don't dominate each other

The algorithm finds a front of non-dominated solutions, which it then sorts for diversity.

Vilfredo Pareto
1848-1923

We use the algorithm NSGA2
(Deb 2002, Bazarov 2005)

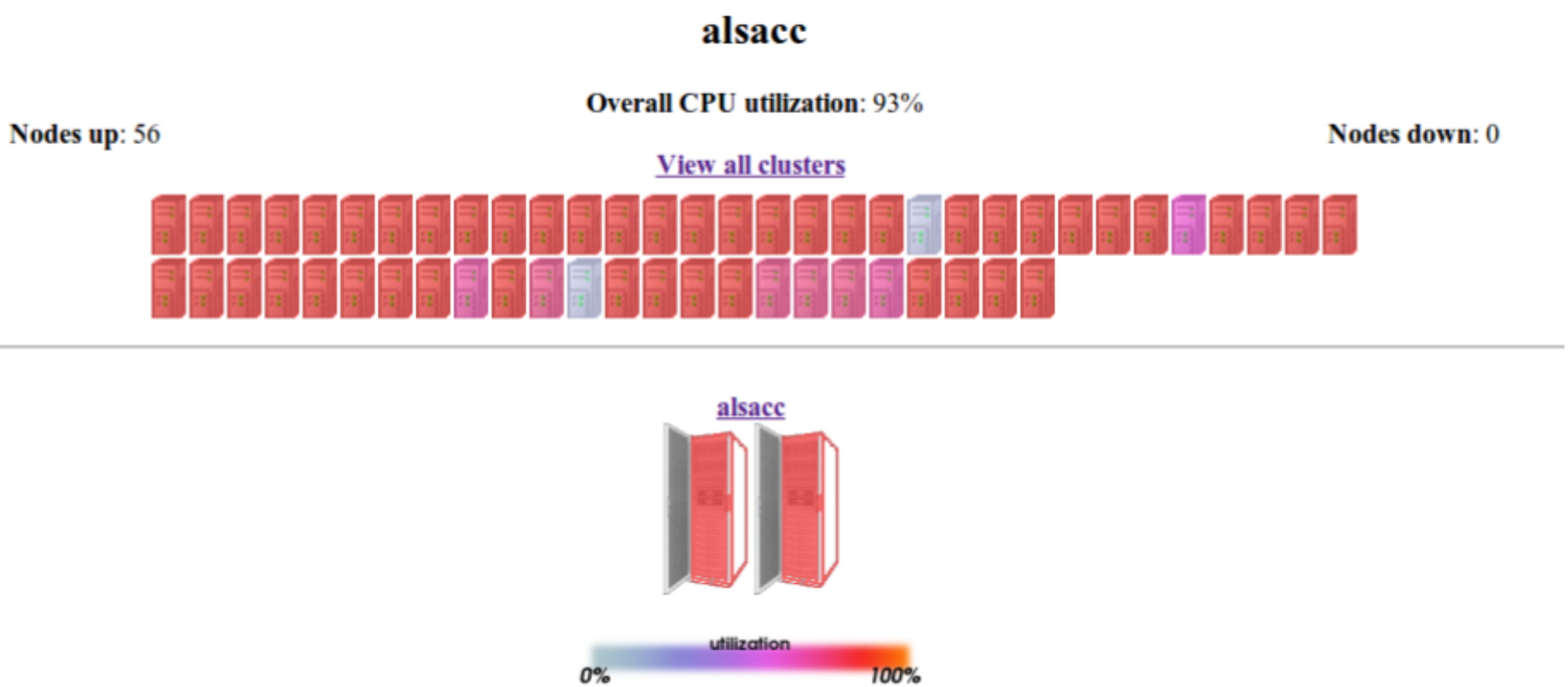
Genetic Optimization

- Widely used family of methods to optimize nonlinear, possibly multimodal, systems
- It is based on the concepts of natural evolution: inheritance, selection, mutation and crossover (mixing of parent "genes")
- Steps of a typical genetic optimizer
  - Randomly generate 1^{st} generation
  - Evaluate 1^{st} generation
  - Sort 1^{st} generation according to objectives, constraints and diversity (this is the point were multiobjective algorithms differ)
  - Repeat
    - Select parents
    - Create children with help of mutation and crossover
    - Evaluate children
    - Sort children (non-elitist) or children+parents (elitist) population
    - Selection
  - Until we reach the number of generations

Implementation at the ALSACC cluster

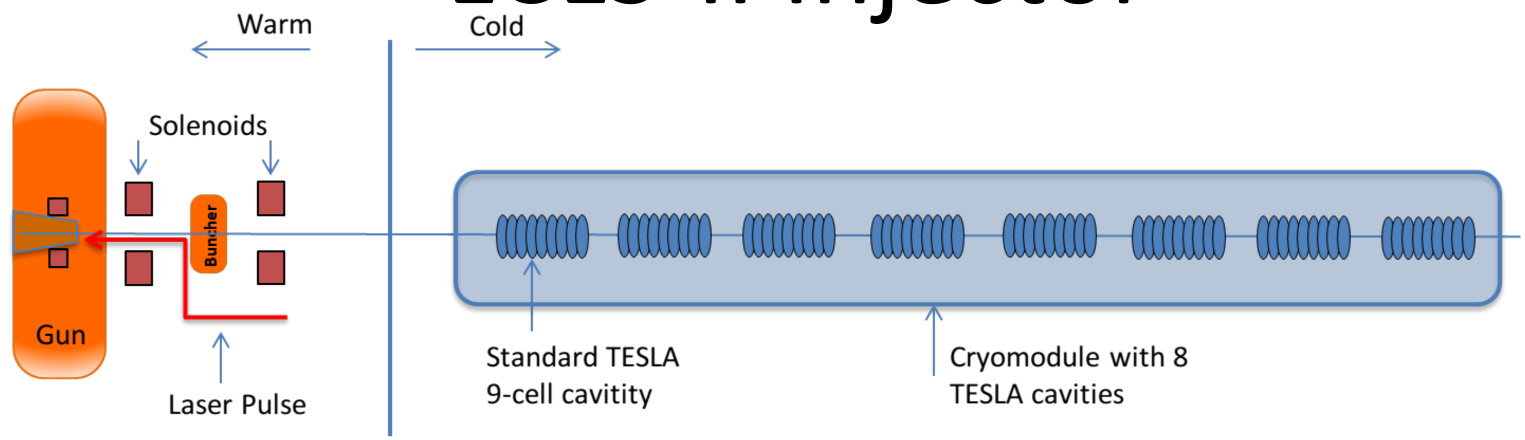
- The most computationally expensive part is the evaluation of each member of the population (5-30 minutes on a single processor).
- No communication needed during evaluation
- Although evaluation itself can be parallel (Ji Qiang et al)
- Need to evaluate multiple potential designs/ setups at the same time.
- Typical convergence times: 300-1000 processor-days

This is our main tool!



EXAMPLES OF OPTIMIZATION

LCLS-II Injector



Solenoid magnet

Warm single-cell RF cavity

Cold multi-cell RF cavity

Laser pulse

Cryomodule

APEX (Advanced Photoinjector Experiment) is a prototype source+ injector for FEL applications. It is very similar to the LCLS-II injector

•1 normal conducting gun @ 186 MHz (186 MHz~=1.3 GHz/7)
•2 solenoids (emittance compensation)
•1 single-cell buncher cavity @1.3 GHz (for compression)
•Accelerating cavities (copper for APEX, superconducting for LCLS-II)

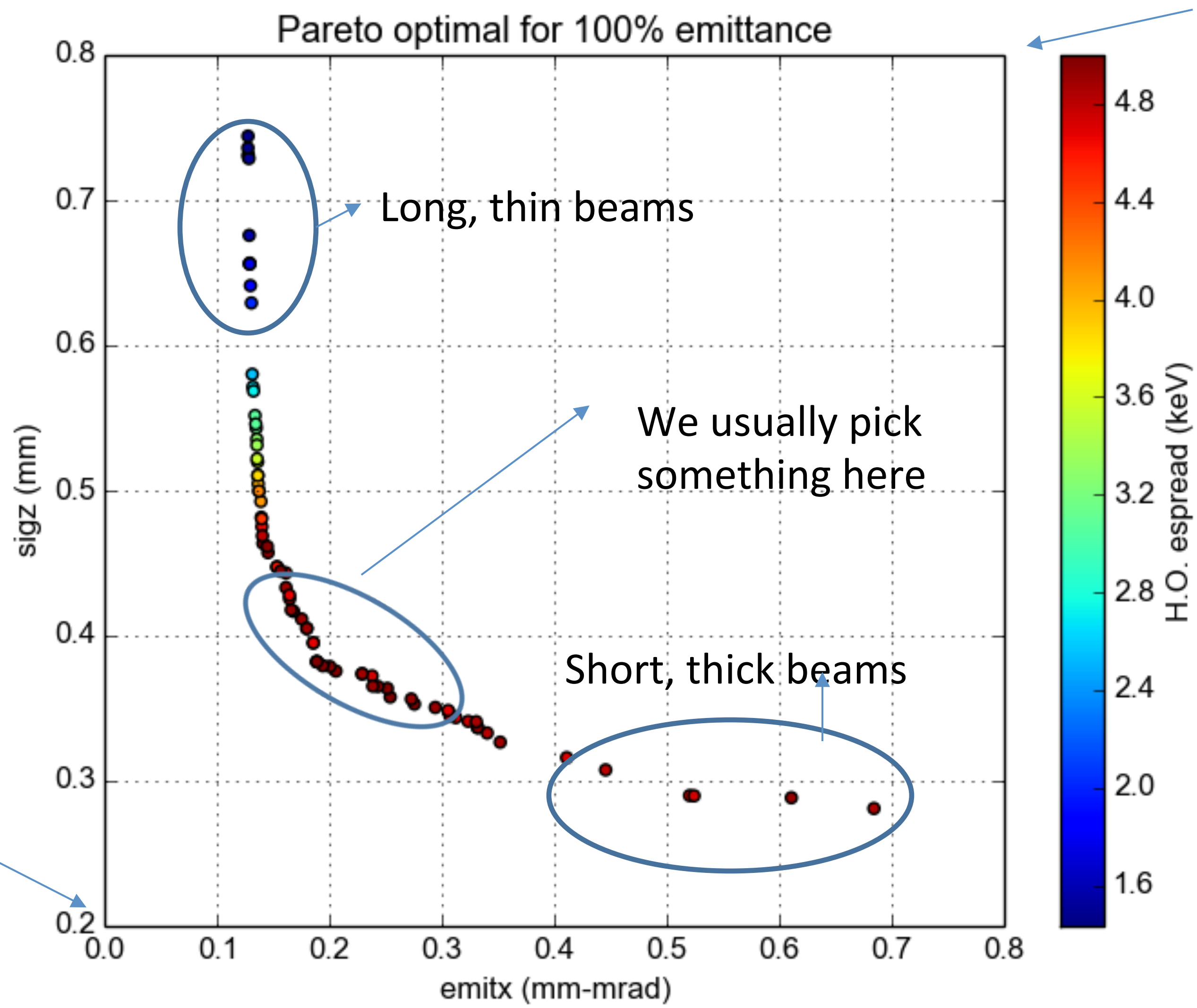
The beam quality, especially the emittance, is determined by the injector (unlike rings)

Available knobs for optimization

Knob	Range	Function
Gun Phase	-15-15 deg	Controls initial bunch length
Buncher on axis peak field	0-4 MV/m	Compression, emittance
Sol 1 B field	0.01-0.2 T	Emittance
Sol 2 B field	0.01-0.2 T	Emittance
CAV 1 on axis peak field	5-25.8 MV/m	Compression, emittance
CAV 2 on axis peak field	5-25.8 MV/m	Compression, emittance
RMS spot size at the cathode	0.05-2 mm	Control intial space charge effects
Bunch length at cathode (plateau with 2 ps rise and fall time)	10-60 ps	Control intial space charge effects

At this stage, only knobs that can be changed during operation are modified. Type and location of components are usually kept constant.

How to pick a solution



Long and thick beams (bad)

Short and thin beams (ideal)

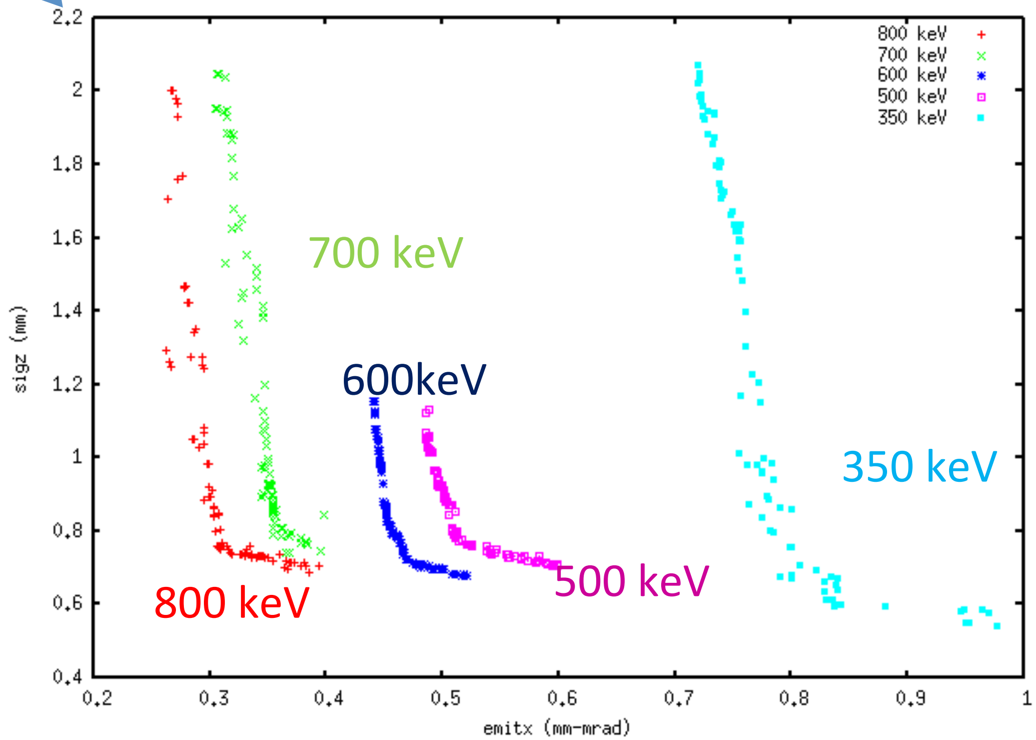
The same approach is taken for the ALS

Variables: strengths of sextupoles
Objectives: Dynamic aperture (size of the beam allowed in the ALS vacuum chamber) for both on and off momentum particle

Changchun Sun

Quickly compare performance of different operating modes

Long and thin beam

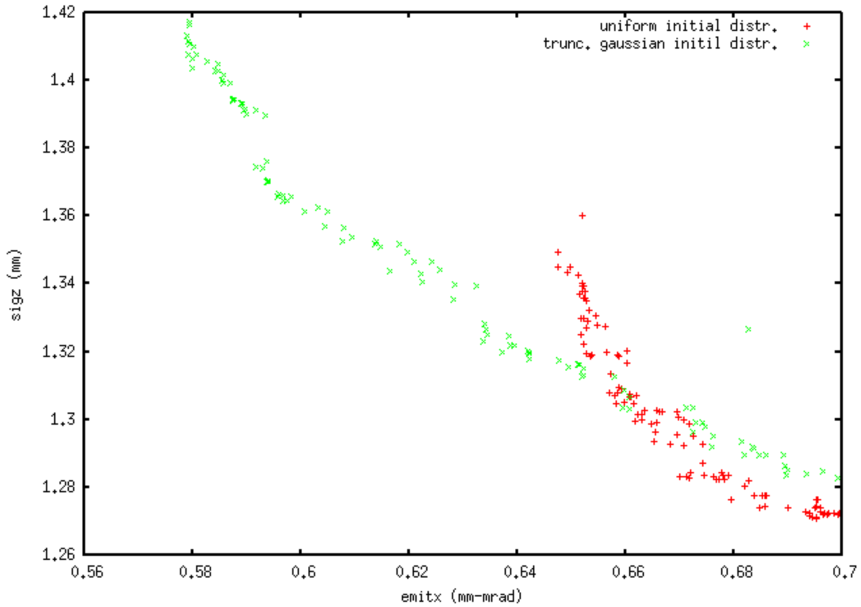


Short and thick beam

Advantage of multiobjective optimization:
Immediately compare different setups, for example beam energy out of the electron source (in this case, they higher the better)

Sometimes we are surprised!

Long and thin beam



Comparison of different initial distributions of the electron beam.

Truncated Gaussian (green) is usually better, but a uniform (red) distribution may be better for high compression

Short and thick beam

THANK YOU!